High Efficiency Thermal Management

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DARPA / MTO High Frequency Integrated Vacuum Electronics (HiFIVE) Industry Day

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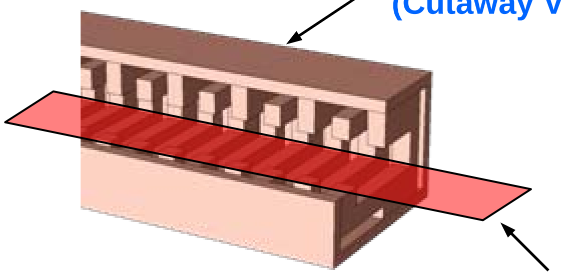
Thermal Issues in HiFIVE

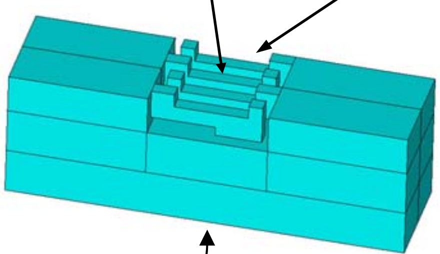
- Combined high power and high frequency lead to high power density in the interaction structure
  - Beam interception, RF losses
- Need to control interaction structure temperatures
  - Thermal expansion (dimensional changes)
  - Thermal cycling (reliability)
  - Outgassing
- Additional thermal constraints (or advantages!) on microfabricated structures & materials suitable for microfabrication vs. standard vacuum electronics
- Beam collector also presents thermal issues
- Attention to high efficiency (compact) thermal management is required

A seedling study on thermal issues was performed at NRL under DARPA/MTO sponsorship

Assumptions for the Seedling Thermal Study



Example Geometry for Thermal Study



View of ½ of the Structure for Thermal Modeling

- Sheet beam with 5:1 aspect ratio*
- Broadband coupled cavity traveling wave structure
- Beam scraping and RF losses contribute to waste heat in general
  - Beam scraping was assumed to be the dominant source of waste heat for the analysis
- 10% beam scraping* total was assumed to occur over the final portion of a typical interaction structure
  - About 1.45 cm length at 220 GHz (based on scaling from W-band devices)

** Note that parameters for this seedling study were for initial estimation purposes only, and that in actual designs the Go/No-Go metrics in the BAA must be used, plus details of the actual combined beam interception and RF losses in performer structures*

220 GHz CW Heat Flux Levels

50 W CW Output Power at 2.5% efficiency or

100 W CW Output Power at 5% efficiency

⇨ 2000 W of beam power

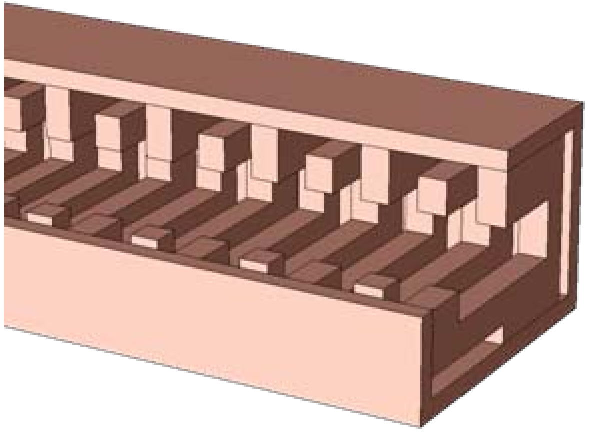
× 10% beam scraping

⇨ 200 W dissipated power in structure

Area = 1.45 cm long x 0.16 cm wide (for 5:1) x 2 (top & bottom) x 0.5 (50% vane coverage)

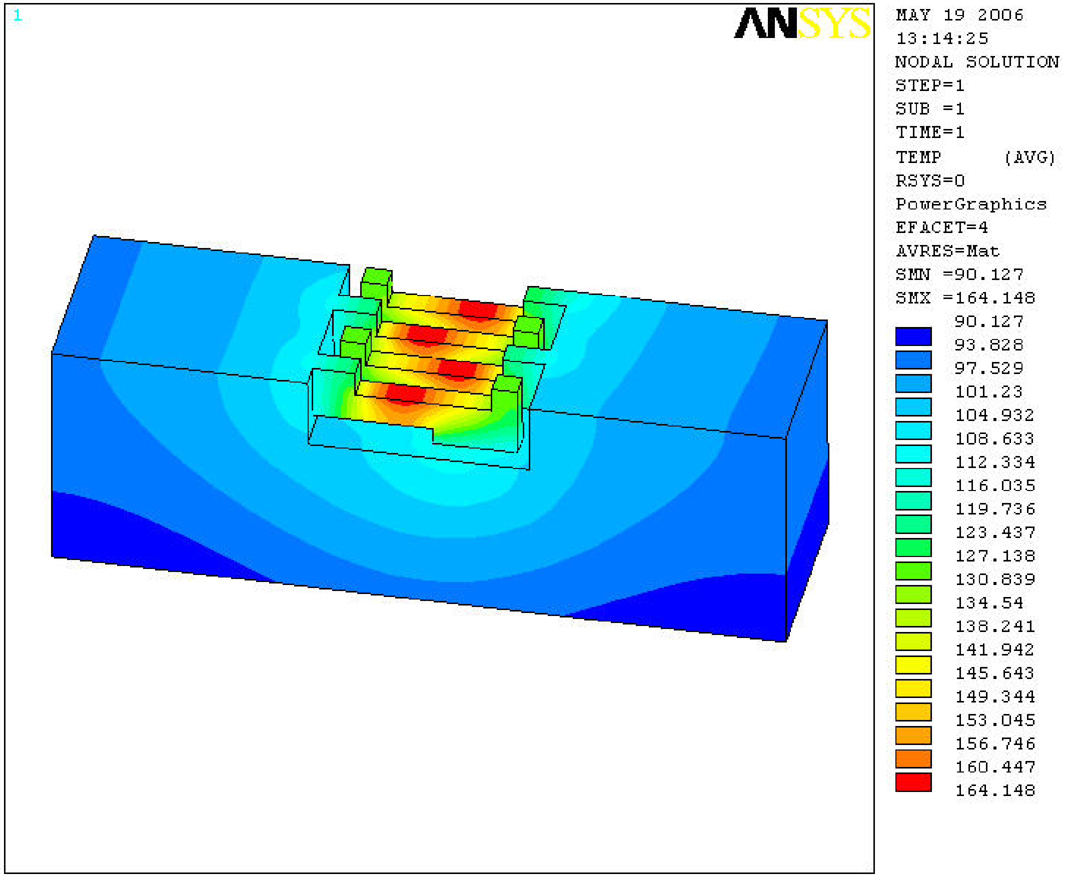
= 0.10 cm2

⇨ 2000 W/cm^2 on vane surfaces



Typical Analysis Results

- Material is copper (κ = 3.85 Wcm^{-1}K^{-1})
- Rear heat transfer coefficient
  - 2.5 Wcm^{-2}K^{-1} @ 20 ^{o}C bulk
  - Consistent with several types of moderately aggressive cooling approaches
- Peak structure temperature 164 ^{o}C
- Rear temperature ~ 97 ^{o}C

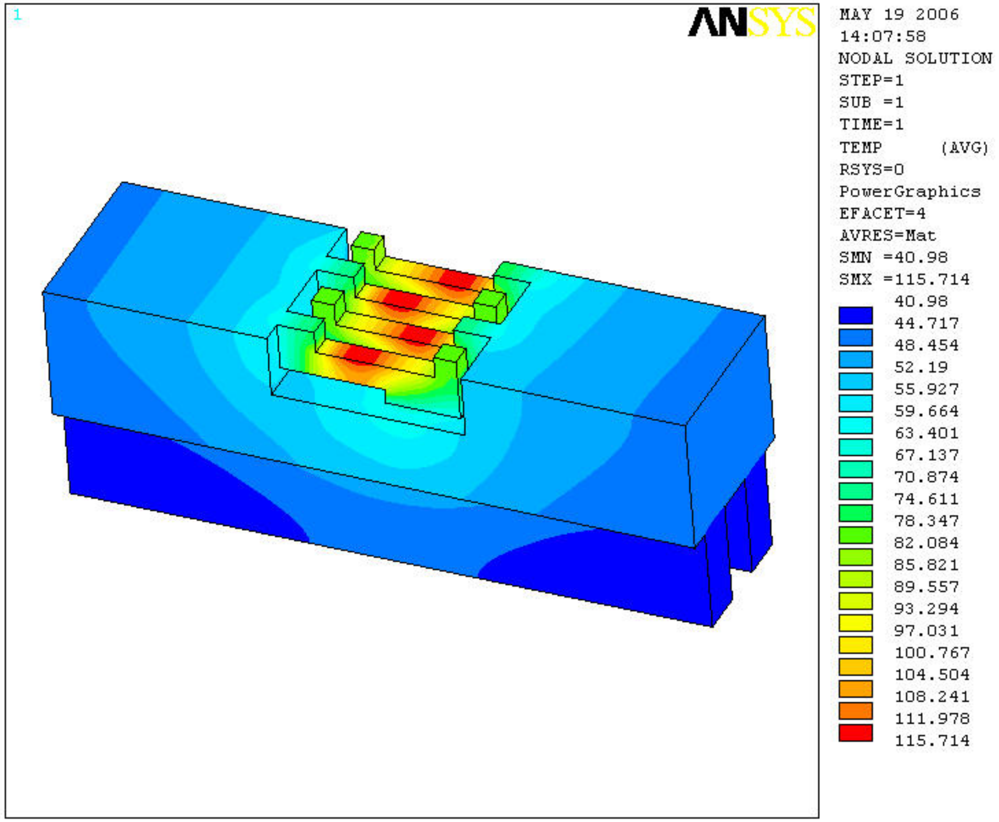


Temperatures (^{o}C) in a 220 GHz copper sheet beam TWT structure, with a CW power density of 2 kW/cm^2 on the vanes (corresponds to 50 W output power if efficiency = 2.5%)

Example with Microchannel-Based Liquid Cooling

- Material is copper ($\kappa = 3.85\ \mathrm{Wcm^{-1}K^{-1}}$)
- Microchannel cooling on rear
  - 250 μm wide by 600 μm tall channels
  - 5 m/s water flow velocity
  - 20 ^{o}C bulk water temperature

- Peak structure temperature 116 ^{o}C
- Peak coolant channel temperature ~ 55 ^{o}C

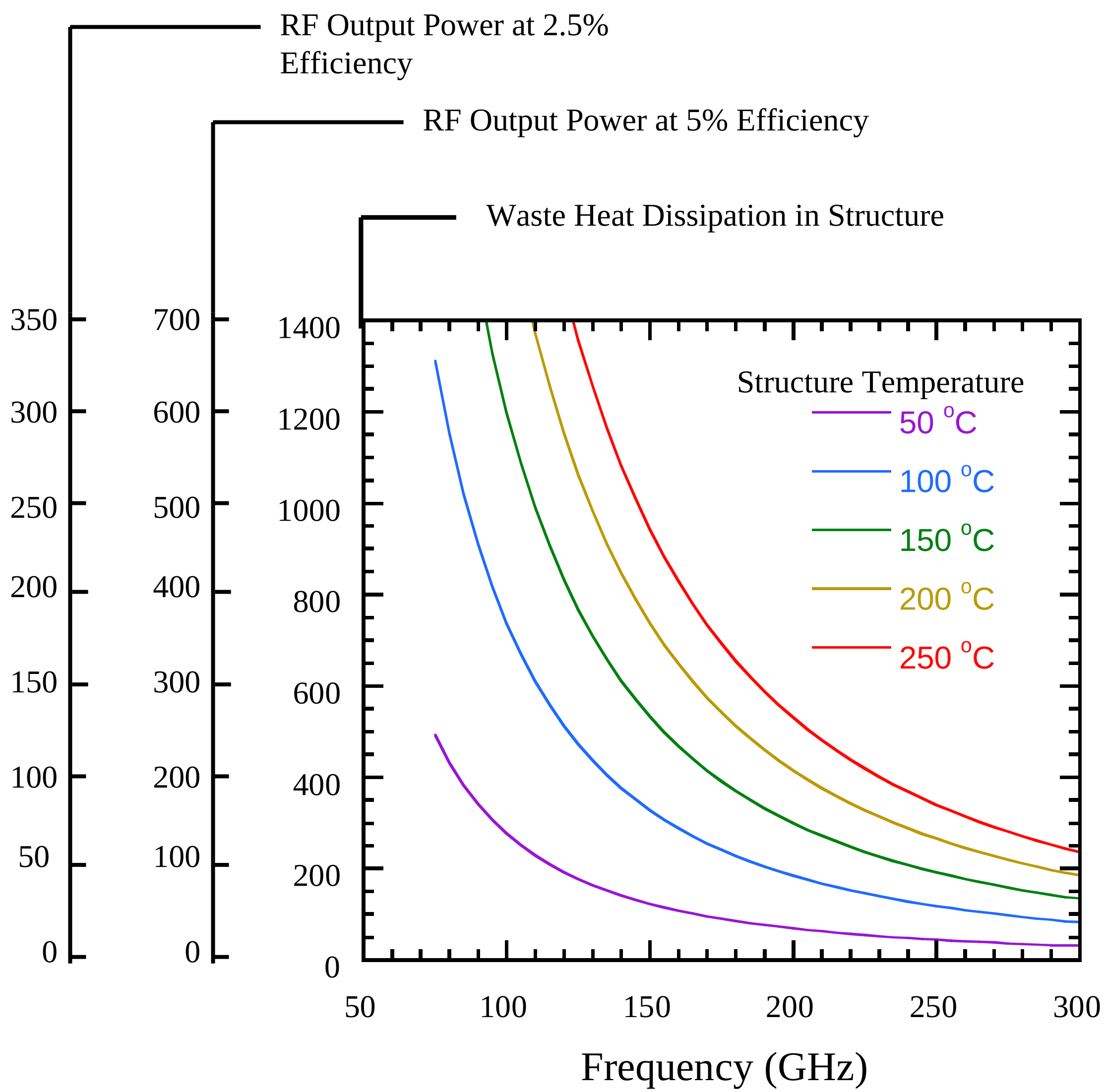


Temperatures (^{o}C) in a 220 GHz copper sheet beam TWT structure using a mircochannel cooler, with a CW power density of 2 kW/cm^2 on the fingers (corresponds to 50 W output power if efficiency = 2.5%)

Scaling of Power Levels with Frequency and Allowable Structure Temperature

- All dimensions assumed to be scaled as $1/f$, where f is the frequency
- Material is copper

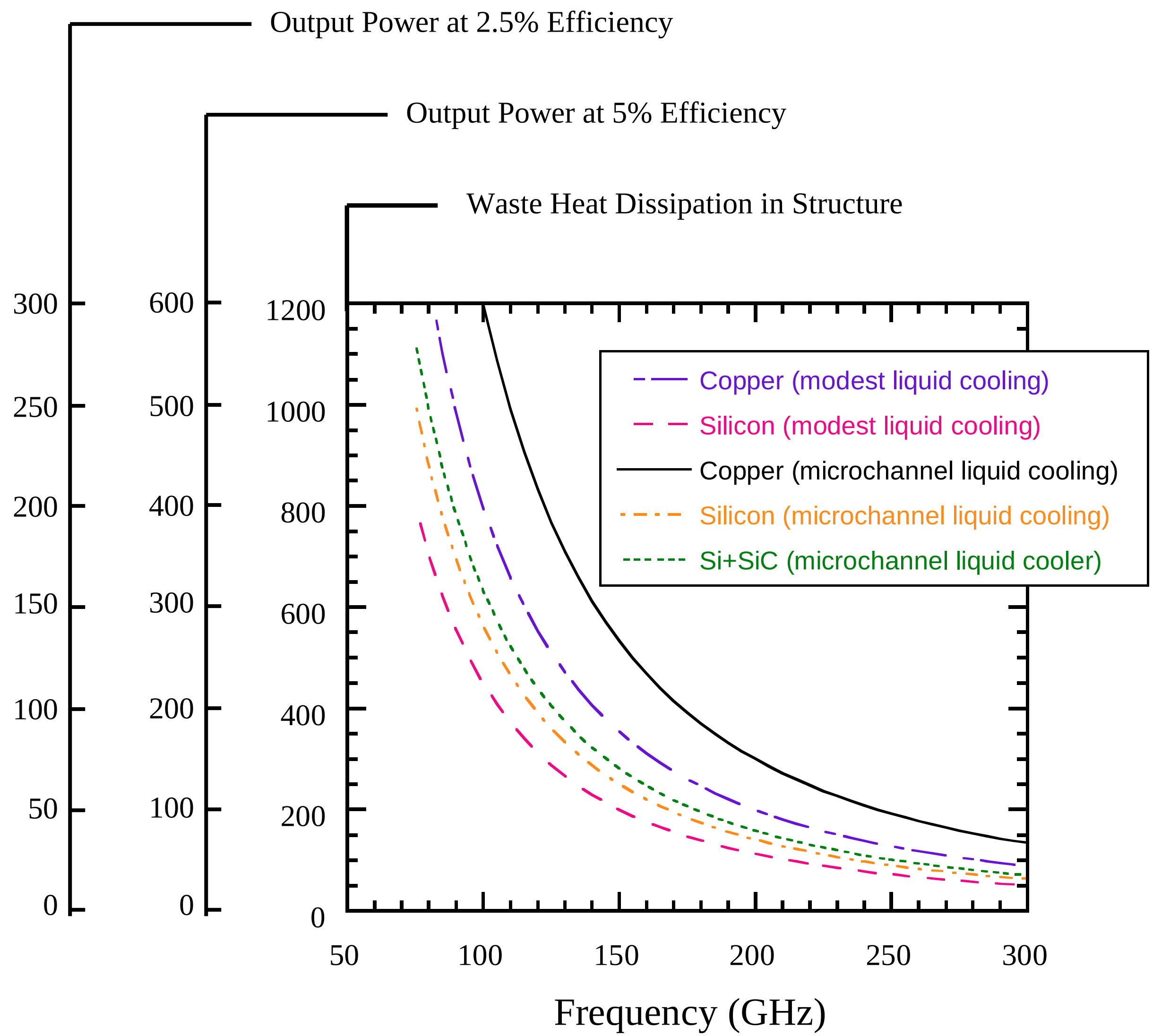
  (κ = 3.85 Wcm^{-1}K^{-1})
- Microchannel cooling on rear
- Microchannel dimensions also scaling as $1/f$
- 10% beam interception assumed
- Curves for various peak structure temperatures are shown



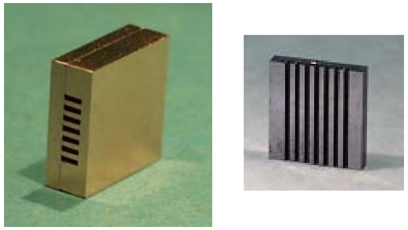
Scaling Curves for Different Structure Materials and Cooling Technologies

- Copper (κ = 3.85 $Wcm^{-1}K^{-1}$)
- Silicon (κ = 1.50 $Wcm^{-1}K^{-1}$)

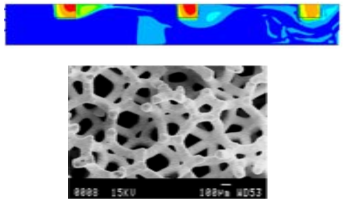
  (has thin metal coating for RF)
- Modest liquid cooling and microchannel cooling both examined
- Silicon on polycrystalline CVD SiC microchannel cooler also examined



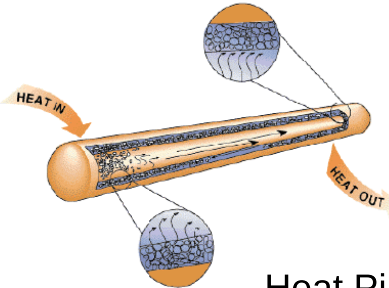
A Potpourri of Possible Thermal Management Techniques

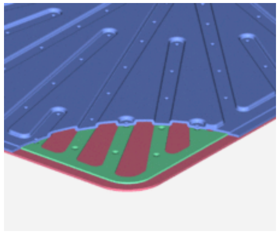


Microchannel Coolers

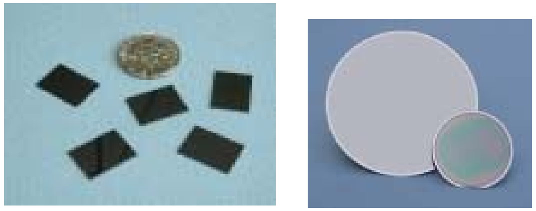


Pin-Fin and Foam-Based Cold Plates

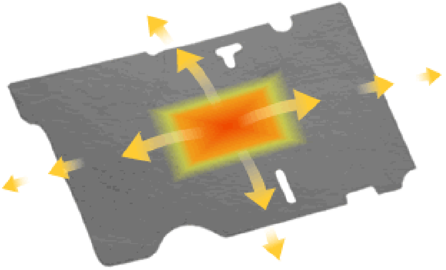




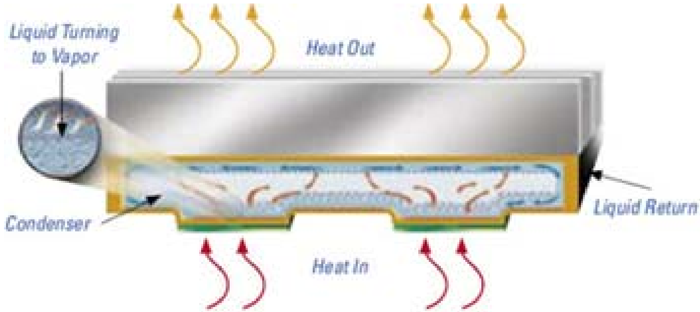
Heat Pipes



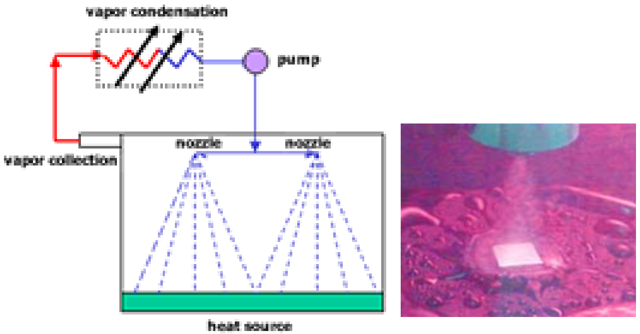
CVD Diamond Structures, Layers, & Composites



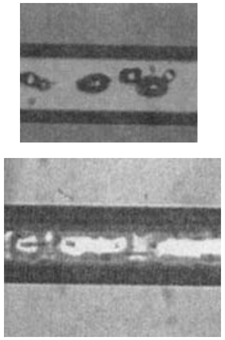
Graphite Layers



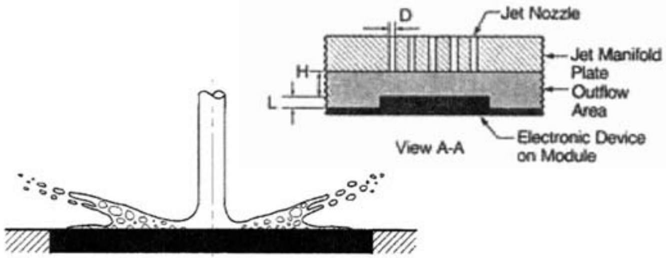
Vapor Chambers



Spray Cooling



Forced 2-Phase Cooling



Liquid Jet Cooling

Summary

- Dissipated power densities can be above 1 kW/cm^2 in the interaction structure
- Beam collector is also a region of concern
- Continuous-wave, reliable device operation is required
- High efficiency thermal management is needed to handle the high heat fluxes in a compact manner
- Example analysis shows that thermal management needs are consistent with several approaches / materials systems
- A wide variety of emerging thermal management techniques could be appropriate